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INFLUENCE OF STATICALLY UNEVEN UNDERLYING SURFACE UPON RADIATION CHARACTERISTICS OF PHASED ANTENNA ARRAY

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Formulation of the Problem. Many studies devoted to an examination of the scattering of a plane monochromatic wave by a statically uneven surface have disregarded the pressing related problem — the influence of the underlying surface irregularities upon the characteristics of antenna radiation. The directional diagram (DD) of an antenna with relatively small dimensions and as high as the suspension (in wavelengths) may be formed by the superposition of the direct antenna field and the field reflected from the surface. The development of methods — which were presented, for example, in [1, 2, 3] — to transfer the results obtained to the case of antennas above an uneven surface is difficult due to the complexity of the methods and the cumbersome nature of the final expressions.

Below we shall make an approximate examination of the influence of a statically uneven surface upon the basic radiation characteristics (observation range [OR] and directive gain [DG]) of a phased antenna array AR based upon a geometric-optical approach to the reflection. We shall assume that the reflection takes place as is shown in Figure 1. This assumption is based upon the fact that, in the case of relatively smooth small surfaces, the reflection is semi-scattered. Assuming that the component which is reflected specularly exceeds the component which is scattered diffusely, we may set the following limitations upon the nature of the irregularities. These limitations will provide the necessary accuracy: (1) the irregularity heights are small as compared with the length of an electromagnetic wave $\sigma < \lambda$, where σ is the mean square deviation of the irregularities; (2) the irregularities are smooth: $\bar{\Lambda}/\sigma \gg 1$, where $\bar{\Lambda}$ is the mean length of the irregularities. These stipulations are closely interrelated — attenuation of one leads to amplification of another.

With these approximations, the influence of the irregularities may be taken into account by introducing random phase advances when rays are reflected from portions of a surface which are located at different levels with respect to the middle section. These phase deviations are equivalent to the phase errors in the aperture of the mirror reflection of an antenna.

The field component which is scattered in a diffused manner, which we shall disregard, decreases with a decrease in the angle of incidence Δ, and for angles which satisfy the well-known Rayleigh criterion this component practically disappears. Therefore, the errors of this method may be primarily indicated in an estimate of the far side lobes, which may be approximately determined due to the solution of the external problem using the Kirchhoff scalar integral method. The underlying surface has the greatest influence upon the OR when the main lobe is placed at small angles to the ground (in this case, we are not interested in the scanning by the main lobe toward the underlying surface). Thus, the OR in the region of the main maximum and the close side lobes may be calculated with an accuracy which is maximum for this method. In the general case, the AR is located at an arbitrary angle to the surface, and has an arbitrary inclination of the phase front in the aperture (Figure 1). The underlying surface is regarded as a conducting infinite plane screen with irregularities of a static nature. The surface is assumed to be uneven only in one direction (in the direction of radiation), i.e., its equation may be written in the form $z = \xi(x)$, where ξ is a random function of x, described by the correlation function $k_\xi(x)$. This representation of the surface makes it possible to reduce the problem to a two-dimensional problem.

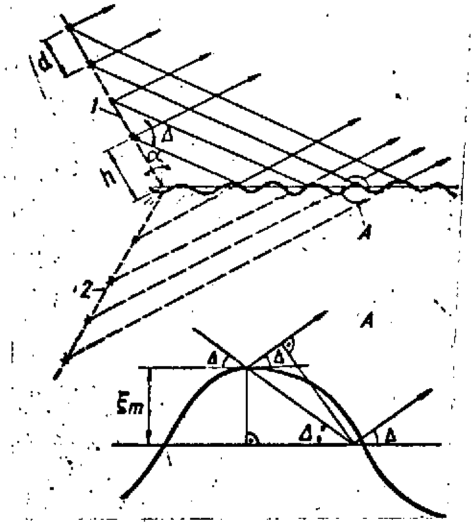

Figure 1.

It is necessary that the random function $\xi(x)$ be stationary and metrically transitive, i.e., it satisfies the conditions of ergodicity. Then, averaging the phase errors, when a section of the surface is sufficiently large within the limits of the first Fresnel zone, we may speak about averaging "over the surface." In the opposite case, averaging over the group of realizations makes sense.

<u>Expressions for directional diagram of an antenna over a statically uneven surface</u>. A field OR antenna in the vertical plane may be written in the form

$$f(\Delta) = f_1(\Delta) + Rf_2(\Delta),$$

where $f_1(\Delta)$ is the antenna OR in free space; $f_2(\Delta)$ — OR of antenna mirror reflection; $R = |R|e^{\beta}$ — Fresnel coefficient for arbitrary polarization.

For the array of isotropic emitters in the case of a uniform amplitude distribution, we have

$$f_1(\Delta) = \sum_{m=1}^{M} e^{i[(m-1)\psi_1+\varphi_1]};\ f_2(\Delta) = \sum_{m=1}^{M} e^{-i[(m-1)\psi_2+\varphi_2]},$$

where in the case of a linear phase advance through the aperture:

$$\psi_1 = kd[\sin(\Delta-\alpha)-\sin\Delta_0],\ \varphi_1 = \frac{h\psi_1}{d\cos\alpha};$$

$$\psi_2 = kd[\sin(\Delta+\alpha)+\sin\Delta_0],\ \varphi_2 = \frac{h\psi_2}{d\cos\alpha}.$$

Here k is the wave number; h — height of suspension of lower emitter above the surface; d — distance between adjacent emitters; m — number of emitters; M — number of emitters in array; α — angle of inclination of antenna aperture with respect to the vertical; Δ — angle in vertical plane; Δ_0 — scanning angle in vertical plane.

In the case of reflection, the phase errors are introduced in the OR of a mirror reflection by a factor having the form $\exp|i2k\xi_m \sin\Delta)$ (ξ_m — random height of irregularity at the point where a ray from the m^{th} emitter is reflected, see Figure 1b). The average OR in terms of strength is

$$\overline{P(\Delta)} = \overline{f(\Delta) f^*(\Delta)},$$

where $f^*(\Delta)$ is a function which is conjugate to $f(\Delta)$. Then

$$\overline{P(\Delta)} = \sum_{m=1}^{M} \sum_{n=1}^{M} \left\{ e^{i(m-n)\psi_1} + |R|^2 e^{i(m-n)\psi_2} \overline{e^{iy}} + R e^{-i[(m-1)\psi_2+\varphi_2(n-1)\psi_1+\varphi_1]} \times \right. \tag{1}$$

$$\left. \times \overline{e^{iv_m}} + R^* e^{i[(m-1)\psi_1+\varphi_1+(n-1)\psi_2+\varphi_2]} \overline{e^{iv_n}} \right\},$$

where $v_{m,n} = 2k\xi_{m,n}\sin\Delta$; $y = v_m - v_n$.

The distribution of the probability density $w(v)$ of a random function $v = 2k\xi\sin\Delta$ is completely determined by the distribution of the probability density $w(\xi)$. We shall assume that $w(\xi)$ of the random function $\xi(x)$ is normal, which corresponds to the majority of real cases. Thus, according to [6],

$$\overline{\exp(\pm iv)} = \exp\left(-\frac{c^2\sigma^2}{2}\right), \tag{2}$$

where $c = 2k\sin\Delta$.

For an arbitrary uneven surface, the correlation function in the general form equals

$$k_\xi(x) = \sigma^2 \exp\left(-\frac{x^2}{\Lambda_0^2}\right)\cos(\varkappa_x x),$$

where $\kappa_x = 2\pi/\bar{\Lambda}$; Λ_0 — interval of correlation of the irregularities; x — distance over the surface. Thus, the correlation function of the phase errors, which are caused by the irregularities, is

$$k_\xi(\tau) = c^2\sigma^2 \exp\left(-\frac{\tau^2}{\tau_0^2}\right)\cos(\varkappa_\tau \tau),$$

where $\kappa_\tau = 2\pi/\bar{T}$; $\bar{T}$ — average period of phase errors in aperture of mirror image of antenna, recalculated from $\bar{\Lambda}$; τ — distance over the aperture of the antenna mirror image; τ_0 — correlation interval of errors in the mirror image recalculated from Λ_0. According to [6], we have

$$\overline{\exp(iy)} = \exp[-c^2\sigma^2(1-\rho_\sigma)], \tag{3}$$

where $\rho_\sigma = \frac{k_\xi(\tau)}{c^2\sigma^2}$ is the correlation coefficient.

Substituting (2) and (3) in (1), after simple transformations we obtain the expression for the average OR

$$\overline{P(\Delta)} = \sum_{m=1}^{M}\sum_{n=1}^{M}\{e^{i(m-n)\psi_1} + |R'|^2 e^{-i(m-n)\psi_2} e^{c^2\sigma^2\rho(m,n)} + + 2|R'|\cos(\beta-\varphi_{mn})e^{-i\psi_{mn}}\}, \tag{4}$$

where in the case of phasing according to a linear law we have

$$\psi_{mn} = kd(m-n)(\cos\Delta\sin\alpha + \sin\Delta_0);\ \varphi_{mn} = kd(m+n-2)\sin\Delta\cos\alpha + + 2kh\sin\Delta.$$

The modulus of the equivalent Fresnel coefficient for an uneven surface is

$$|R'| = |R|e^{-\frac{c^2\sigma^2}{2}}.$$

Thus, the influence of the irregularities reduces the Fresnel coefficient modulus and leads to the appearance in the OR of a factor caused by the correlation of the surface irregularities. If the correlation of the irregularity is small (slightly rough surface) and it may be disregarded, the average OR in terms of power acquires the form

$$\overline{P(\Delta)} = f_1^2(\Delta) + |R'|^2 f_2^2(\Delta) + 2|R'|f_1(\Delta)f_2(\Delta)\cos(\beta - 2kH_{cp}\sin\Delta) + + M(|R|^2 - |R'|^2), \tag{5}$$

where

$$f_1(\Delta)=\frac{\sin\left(\frac{M\psi_1}{2}\right)}{\sin\left(\frac{\psi_1}{2}\right)};\quad f_2(\Delta)=\frac{\sin\left(\frac{M\psi_2}{2}\right)}{\sin\left(\frac{\psi_2}{2}\right)};\quad H_{cp}=\left(\frac{M-1}{2}d+h\right)\cos\alpha.$$

The correlation interval of the phase errors in the aperture of the mirror reflection τ_0 at small angles of inclination of the curtain antenna array α changes between $0 \leq \tau_0 \leq \infty$ when $0 \leq \Delta \leq 90°$. At small angles of Δ, when $\tau_0 \leq d$, the errors in the emitters of the mirror image are barely correlated and the dispersion $c^2\sigma^2$ is small. At large Δ, when $\tau_0 \gg d$, the influence of the errors is greatly attenuated as compared with the case when there is no correlation. The larger the correlation interval Λ_0, the smaller is the influence of the phase errors caused by irregularities, as compared with the case of reflection from noncorrelated irregularities.

In the general case, the dispersion of the OR deviations from the average value $\sigma_p^2 = \overline{P^2(\Delta)} - \overline{[P(\Delta)]^2}$. The right side of the equation is determined from (1) and (4). The reduction in DG($\bar{g}$) caused by the influence of the irregularities is also found from (4).

<u>Analysis of calculation results</u>. By way of an example, let us examine vertical antenna arrays containing 4 and 16 stages of emitters, with a distance between of $d = 0.5\lambda_{min}$ (λ_{min} — minimum wavelength of the operational antenna range) and the height of the suspension of the lower stage $h = 0.6\ \lambda_{min}$ (Figure 1). Vibrators having an arm length of $l = 0.25\ \lambda_{min}$ may be used as the emitters. Behind the curtain of vibrators at a distance of $d_e = 0.35\ \lambda_{min}$ there is an aperiodic reflector which forms the monodirectional radiation of the antenna. In this case, the OR is formed with the active participation of the underlying surface.

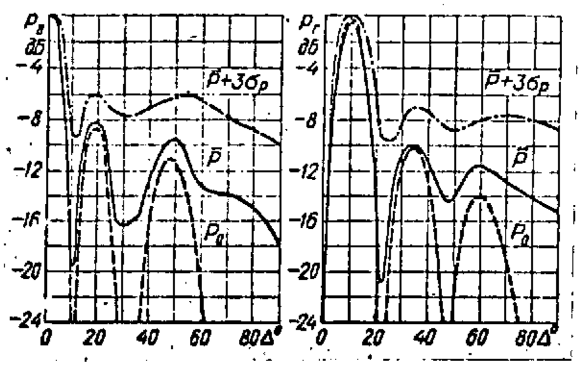

Figure 2.

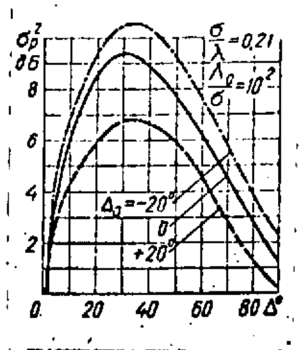

Figure 3.

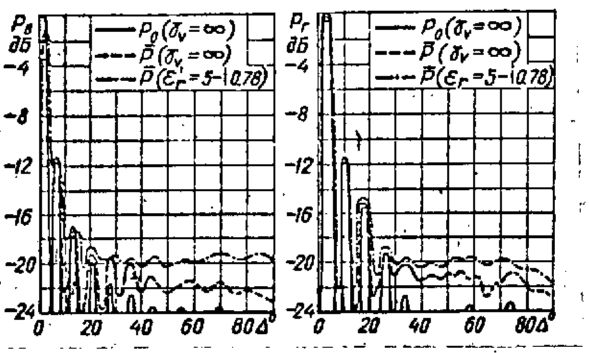

Figure 4.

Assuming that the mirror component of the field reflected from the surface is greater than the scattered component, by at least one order of magnitude, on the basis of the results derived theoretically [1, 4] and experimentally [5], we may impose the following limitations on the irregularity:

$$\frac{\sigma}{\lambda} \lesssim 0.3; \ \frac{\bar{\Lambda}}{\sigma} \gtrsim 30.$$

For an ideally conducting surface ($\gamma_V = \infty$) we calculated the normed OR of a four-stage array for the case of vertical and horizontal polarization of radiation, their deviation from the average value (Figure 2) and dispersion (Figure 3). The average OR of a sixteen-stage array are given in Figure 4 in the case of nonideal conductivity of the surface.

A comparison of the OR above a smooth (P_0) and an uneven ($\sigma/\lambda = 0.21$; $\Lambda_0 = 10^2\sigma$) surface ($\bar{P}$) shows that the irregularities cause an expansion of the main lobe, migration of the nulls, and an increase in the side lobes. A slight movement of the main lobes toward the surface is observed.

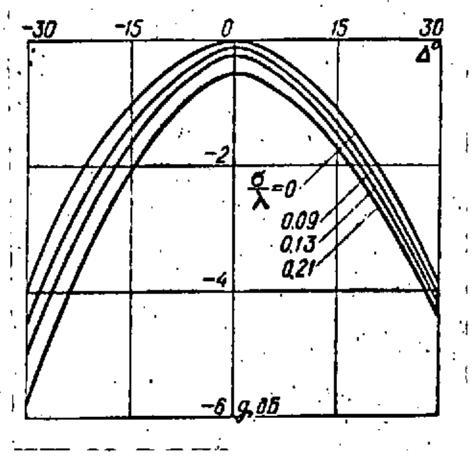

Figure 5.

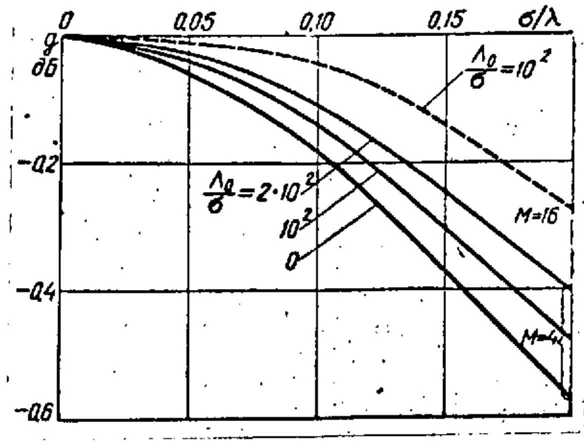

Figure 6.

It may be seen from Figure 3 that the average OR has small deviations in the region of the main maximum and the far lobes, and has large deviations in the region of the near side lobes. In the case of deviation of the OR main lobe from the surface, distortions caused by the irregularities are greatly attenuated. This is also apparent in Figure 5, which shows the influence of the angle of orientation for the OR main lobe of a four-stage AR upon the reduction in DG. The dependence of a DG reduction on the normed, mean square deviation of the irregularities is shown in Figure 6 for different correlation intervals. A decrease in the irregularity correlation interval lowers the antenna directivity.

It may be seen from a comparison of the reduction in the DG of a four- and sixteen-stage array (Figure 6) that, with an increase in the vertical dimension of the aperture when the aperture step is retained, the influence of irregularities in the underlying surface decreases.

In the case of ideal conductivity of an uneven surface, there is no difference in the influence upon radiation which is polarized horizontally and vertically. In the case of nonideal conductivity, the irregularities change the modulus of the Fresnel coefficients (Figure 7). Thus, the deterioration is much greater in the characteristics of emission for an array with horizontally polarized emitters (Figures 4 and 8).

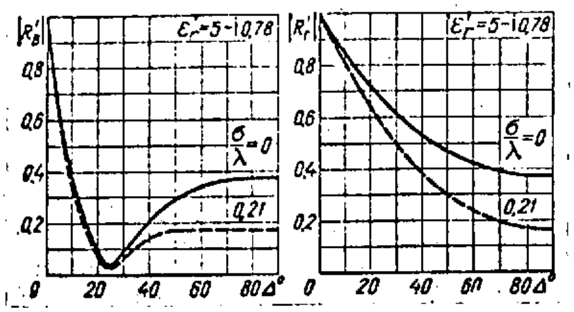

Figure 7.

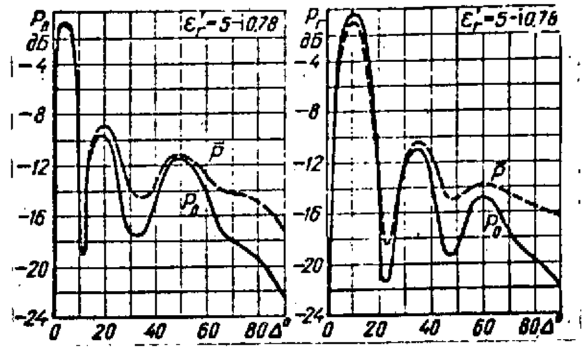

Figure 8.

Conclusion. Under the approximations of geometric optics, expressions were obtained for the average OR and its dispersion, making it possible to establish the influence of a statically uneven underlying surface upon the antenna radiation characteristics.

Graphs were obtained which characterized the deterioration of the directional properties of scanning AR, whose OR is formed with the use of an underlying surface having differing conductivity in the case of vertical and horizontal polarizations of radiation and different vertical dimensions of the AR in the wavelengths. The irregularities distort the OR and decrease the antenna directivity. Calculations of the OR dispersion show that the main distortions are observed in the region of the side lobes. Raising the OR main lobe upwards reduces the influence of the irregularities.

When there is an increase in the antenna directivity (with an increase in the vertical dimension of the AR aperture), the influence of the irregularities decreases. It also decreases with an increase in the correlation interval.

In the case of nonideal conductivity of the underlying surface, the influence of the irregularities is more pronounced in horizontally polarized radiation and less pronounced in vertically polarized radiation.

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